

PKS 1830-211: A Possible Compound Gravitational Lens

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Measurements of the properties of gravitational lenses have the power to tell us what sort of universe we live in. The brightest known radio Einstein ring/gravitational lens PKS 1830-211¹, whilst obscured by our Galaxy at optical wavelengths, has recently provided a lensing galaxy redshift of 0.89 through the detection of molecular absorption in the millimetric waveband². We report the detection of a new absorption feature, most likely due to neutral hydrogen in a second redshift system at $z=0.19$. Follow-up VLBI observations have spatially resolved the absorption and reveal it to be concentrated toward the N¹, compact component, but mostly covering the lower surface brightness ring. This new information, together with existing evidence of the unusual VLBI radio structure and difficulties in modeling the lensing system, points to the existence of a second lensing galaxy along our line-of-sight and implies that PKS 1830-211 may be a compound gravitational lens.

The strong, ~ 10 Jy, flat-spectrum radio source PKS 1830-211 was found in 1991 to be an Einstein ring/gravitational lens¹ and remains the brightest such object found in the radio sky by almost 2 orders of magnitude. While the interpretation of the source as a gravitational lens beyond the Galaxy³ is secure, it lies in a crowded and heavily obscured field close to the Galactic centre and so far all efforts to identify optical counterparts either for the lensing galaxy or the lensed source have been unsuccessful^{4,5}. In particular, the failure of optical measurements to furnish any redshifts has driven the search for these critical parameters into the radio spectrum.

The symmetric morphology of the source, comprising two compact, flat-spectrum components of similar brightness located on opposite sides of a 1 arcsecond ring, immediately suggests a close alignment of the lensed source behind the lensing mass. Moreover there is evidence of unusually high rotation measures in some parts of the source which argues that the lensing galaxy is probably a gas-rich spiral⁶ and suggests the possibility of detecting molecular absorption.

Accordingly we undertook survey on 10 and 11 June 1995 for redshifted H¹ and OH absorption with the Parkes 64 m radio telescope, as part of a cooperative observation programme with the Project Phoenix group⁷. The Project Phoenix receiver and signal processing equipment were used to cover a frequency range of 995 to 1675 MHz, nicely complementing a previous absorption search over the frequency range 400-1000 MHz at Greenbank,

which yielded a negative result. Our observations excluded the two intervals 1535-1635 MHz and 1165-1175 MHz because of excessive interference. Although interference of both terrestrial and satellite origin was profuse over most of the remaining band, it was generally of very narrow bandwidth and easily recognizable, and did not greatly impede the search.

We detected only a single absorption feature with two sub-components of similar amplitude, centred at 1191.1 MHz with an overall line width of approximately 50 km/s (Figure 1a). The absorption feature was detected with comparable strength on two consecutive days. On the second day, observations of PKS 1830- 211 were bracketed with those of PKS 1921- 293, a nearby source of similar flux density. No evidence of the absorption feature was seen in this comparison source.

VLBI observations were made on 18 September 1995 with four telescopes of the Australian Long Baseline Array (LBA)^{9,10}; Hobart, Mopra, Parkes and five antennas of the Australia Telescope Compact Array (ATCA) acting as a phased array. S2 recorders¹¹ were used, operating in dual polarization (LCP and RCP) with 4 MHz bandwidth centred on 1191.0 MHz. Correlated visibilities between all 6 antennas of the ATCA were also recorded to produce an improved total-power spectrum (figure 1b).

PKS 1830- 211 was observed over an 8 hour period interleaved with a bandpass calibrator. The VLBI data were correlated at the ATNF VLBI correlator¹². No correlated flux was detected on the long (> 4 M λ) baselines to Hobart owing to interstellar scattering at this low frequency¹³.

Our VLBI image in figure 2 is similar to an earlier 2.3 GHz VLBI image¹ and shows the two compact components of PKS 1830- 211, but little of the low brightness ring which is heavily resolved at this resolution. Figure 2 also shows the absorption spectrum of each component, clearly demonstrating that the two sub-features of the absorption system obscure different parts of the source. The low velocity component is completely resolved and therefore must be obscuring only the extended ring while the high velocity component is resolved only partially and covers the NE component but is weak or absent in the SW component. These observations also allow us to infer that the angular size of the absorbing features must be greater than a few tenths of an arcsecond.

A molecular absorption system at a redshift of 0.88582 has already been found in this source², and is argued to arise in an intervening galaxy rather than in the lensed object. We believe that our detection constitutes a second

absorption system in PKS 1830-211 and is probably H I absorption in an intervening galaxy at a redshift of $z = 0.92640 \pm 0.0001$. In support of this we note that there are no catalogued H I lines near 2246 MHz, the rest frequency of our observed absorption if it belongs to the $z = 0.89$ system. Further, we observed the bright Galactic sources Sgr B2, Ori KL, and IRC 10216 with the 26 m telescope at Hobart to search for a possible unlisted transition at this frequency, and detected nothing above an rms noise level of $\sim 0.1\%$ of the continuum. Moreover, our detection appears to lie in front of the NE component whilst the $z = 0.89$ absorption is apparently confined to the SW component². Our absorption feature also displays velocity structure not seen in the $z = 0.89$ absorption profiles.

The interpretation of the feature in figure 1 as OH is unlikely for two reasons. Firstly, the spectrum shows none of the 'satellite' profiles typical of OH absorption and secondly, we see no evidence of absorption at 1016 MHz corresponding to H I at the same redshift, which we would expect to be clearly visible. Neither can this be an hydrogen recombination line as we would have detected many such lines across the band and did not.

Wiklind and Combes (priv. comm.) report no evidence of molecular absorption in PKS 1830-211 at $z = 0.9$ in their SEST observations. However this is not totally unexpected as the total solid angle subtended by the source at these high frequencies is small ($\sim 1 \text{ mas}^2$) and hence the probability of intersecting a dense molecular cloud along the line of sight is presumably quite modest.

The absorption features seen in figure 1 is very similar in both width and column density to that found in the lens system 0218+35"¹⁴, which is convincingly argued to arise from H I absorption in the lensing galaxy, probably a spiral galaxy seen nearly edge-on. We favour a similar interpretation for the absorption in PKS 1830-211, with the line of sight intercepting several cold clouds in a gas-rich spiral at $z = 0.9$. The two features seen in the absorption profile may well correspond to two spiral arms seen nearly superposed, both of which partially obscure the ring and one of which obscures the NE compact component. Such a picture is entirely consistent with the properties of H I clouds and galaxy dynamics observed within our own Galaxy.

Independent evidence for a considerable amount of material along the line of sight is suggested by the unusually high rotation measure seen in the NE component^{6,15}. Furthermore, the observed downturn in total flux density of PKS 1830-211 below 1 GHz¹⁶ implies significant free-free absorbing material

obscuring the non-compact structure which emits a steep spectrum and cannot be self-absorbed.

While the 111 absorption toward PKS 1830-211 indicates the presence of a galaxy-scale mass at $z = 0.19$, this does not infallibly imply *a priori* that gravitational lensing is taking place at this redshift, any more than it does for the $z = 0.89$ system. That lensing of some kind is taking place is beyond dispute given, for example, the short time delay seen in the flux density variations of the two compact components—a most improbable effect in any non-lensed interpretation. It seems almost certain therefore, that at least one of the two redshift systems at $z = 0.19$ and $z = 0.89$ is partaking in the lensing and there is further evidence that both systems may be involved.

Firstly, the lens evinces a quite paradoxical appearance at high resolution. VLBI images made over a 3 year period^{18,19} show the SW component to be unresolved at \sim milliarcsecond resolution while the NE component shows a well resolved linear structure. This difference in morphology of the two components is too long-lived to be due to the difference in propagation times to the two components, estimated to be no more than a few tens of days^{6,17}. The results presented here suggest that the second absorption system at $z = 0.19$ may be responsible for this striking disparity in the two images by causing additional lensing distortion of the NE image, thus forming a compound gravitational lens. Secondly, attempts to model PKS 1830-211 with a single, simple gravitational potential have achieved only modest success, and have produced markedly different models. The models developed by Nair *et al.*⁶ and by Kochanek *et al.*²⁰, for example, differ in a number of material respects, not least in the time delay between the two compact components, which has the opposite sign in the Nair *et al.* model to that inferred from the Kochanek *et al.* model.

The presence of a second lensing galaxy in this system adds an extra layer of complexity to any lensing model. This galaxy is likely to influence the light travel time through the NE component and so must be considered before a determination of H_0 from the time delay can be made. It is important therefore to estimate the mass and position of the $z = 0.19$ galaxy. We are unable to obtain this information from our data. However polarization images of PKS 1830-211 at two or more frequencies to map rotation measure would help to pinpoint the position of the galaxy.

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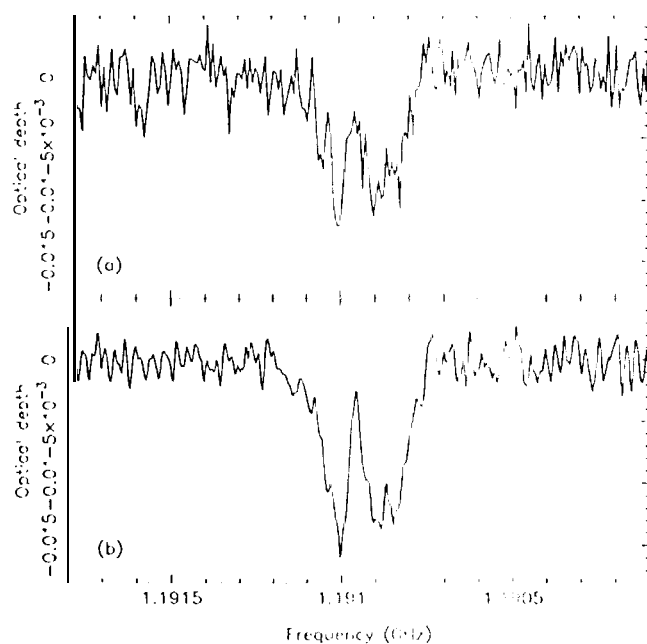


Figure 1: a) Discovery spectrum taken at Parkes with the Project Phoenix SETI Receiver. b) Confirmation spectrum taken at the ATCA during our VLBI observations.

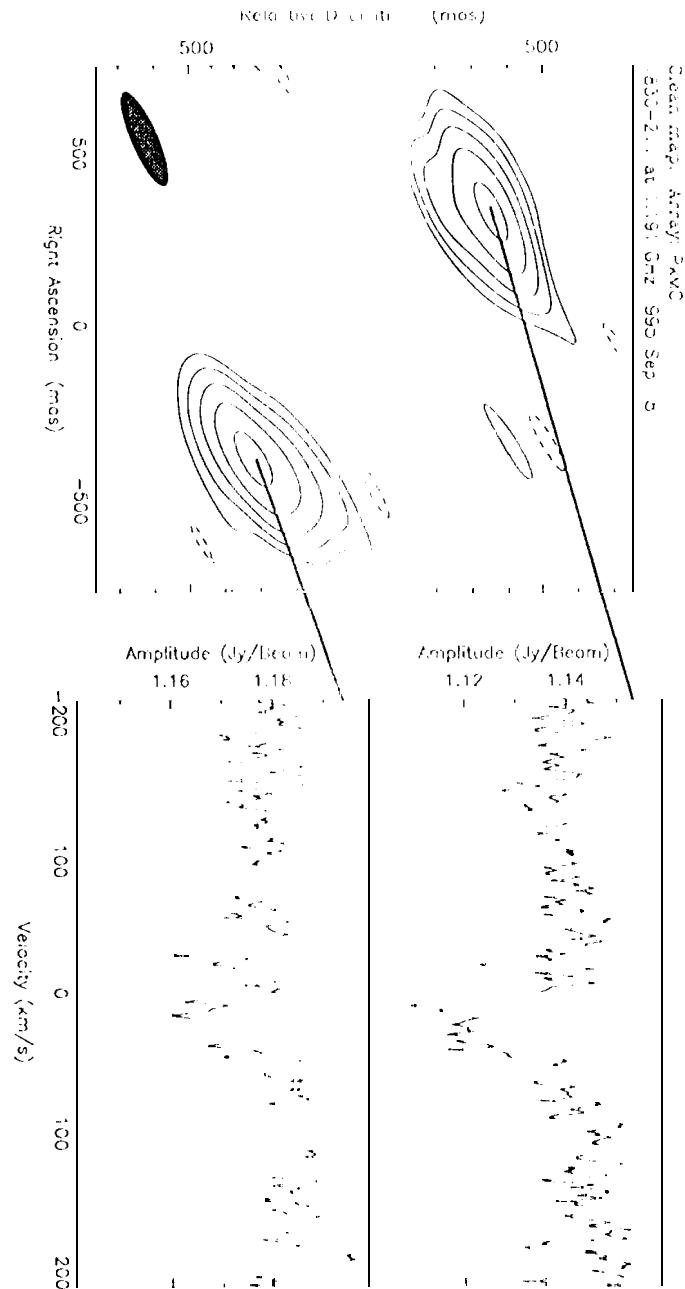


Figure 2: Our VLBI continuum map of PKS 1830-211 (left). The restoring beam is 294 by 75.2 mas and the contours are at 5, 10, 20, 40 and 80% of the map peak which is 1.27 Jy/beam. Also shown here are the spectra at the positions of the two continuum components (right).